Journal of the Indian Society of Remote Sensing
https://doi.org/10.1007/s12524-021-01445-z

RESEARCH ARTICLE

A Study of Rocket Exhaust Plume in the Lower Atmosphere using Geo-Imaging High Resolution Camera (GHRC) On-board Indian Geostationary Satellite

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Received: 8 March 2021 / Accepted: 12 October 2021
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Abstract
Rocket exhaust plumes in atmosphere are remarkable phenomena that can be clearly seen from both the Earth's surface and space. A huge number of dispersed particles within the exhaust plume provide sufficient scattering of solar radiation that can be registered by photographic cameras from ground or space. In the present study, we have analysed rocket exhaust plumes from the Geosynchronous Satellite Launch Vehicle (GSLV) MK-II F11 carrying the Geostationary SATellite (GSAT)-7A payload using the Geo-imaging High Resolution Camera (GHRC) on-board GSAT-29 satellite for the purpose of probing atmospheric states. This study deals with analysing the initial rocket plume produced by the GSLV vehicle launched from Satish Dhawan Space Centre, Sriharikota on 19 December, 2018. Approximately 2211 frames acquired by the GHRC instrument at $\sim$ 1.5 frames per second around the time of GSAT-7A launch were processed, rocket exhaust plume was detected and motion vectors of exhaust plume were traced to estimate horizontal components of wind velocity at different altitudes. GHRC estimated U component of wind ranged from $-$ 7.1 m/s at 200 hPa to $+$ 4.0 m/s at 100 hPa with lower values close to surface. V component of wind ranged from $-$ 4.8 m/s at 900 hPa to $+$ 8.6 m/s at 400 hPa with intense shear between 200 and 100 hPa levels. Comparative analysis of results obtained from satellite data with Weather Research and Forecasting modelled wind fields showed a good match. For the first time in India, we analysed the dynamics of rocket exhaust plume in the troposphere and lower stratosphere using satellite-mounted imaging camera on a geostationary platform and demonstrate its application in obtaining atmospheric wind profile. This study also demonstrates the unique high-temporal capability of GHRC for its use in large-scale smoke/plume detection.

Keywords Geostationary imaging · GHRC · Rocket exhaust · Smoke plume · Wind profile

Introduction

The launches of powerful space-ferrying rockets and the exhaust of launch vehicle engines are followed by the injection of large quantity of combustion products into the atmosphere. These combustion products contain both gas and dispersed solid components, which in turn develop clouds of gas and dust in the atmosphere having specific geometric and dynamic features. Development of such artificial formation in the atmosphere is produced by the scattering of sunlight from the combustion products as well as their interaction with constituents of the atmosphere (Dalin et al., 2013). Rocket exhaust plumes are unique and striking atmospheric phenomena that can be clearly seen from both the Earth's surface and space. A huge number of dispersed particles provide sufficient scattering of solar radiation during its interaction with the rocket exhaust plume in the ultraviolet, visible, and infrared spectral ranges that can be registered by spectrometers and radiometers from space or by photographic cameras from the ground. Detailed tracing and analysis of the exhaust plume from a rocket's initial trajectory is a useful technique both scientifically and diagnostically. It can provide detailed information on the atmosphere's mean winds, wind shears, turbulent regime, and physical state over a wide altitude range. Moreover, investigations of these

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Published online: 23 October 2021

optical phenomena lead to the study of dynamic processes occurring in the atmosphere, anthropogenic pollution of near-Earth space and interaction processes of the exhaust polluting material with the environment.

Investigations into the dynamic and structural features of the large-scale artificial formations due to rocket exhaust in the upper atmosphere have been carried out by various authors. In particular, it has been shown that the characteristic velocity of expansion of gas-dust clouds formed by rocket exhausts is 1–2 km/sec, and their sizes can reach several hundreds of kilometres in a diameter. Interaction of the gas phase of combustion products with the atmospheric components results in changes to the ion-molecular reactions that also can result in the occurrence of anomalies in luminescent phenomena of the upper atmosphere (Mendillo et al., 1975). The analysis of the optical recordings gives a general estimation of the lifetime of the phenomena as well as conclusions related to the physical mechanisms involved therein. A huge number of dispersed particles provide sufficient scattering of solar radiation and of geocoronal hydrogen airglow in the ultraviolet, visible, and infrared spectral ranges to be registered by spectrometers and radiometers from space (Meier et al., 2011; Siskind et al., 2003; Stevens et al., 2002) and by photographic cameras from the ground (Chernouss et al., 2005; Molchanov & Platov, 2011; Platov et al., 2011). However, there is no analysis or the literature available on study of rocket exhaust plumes from the space-based observations, at least in India.

Satish Dhawan Space Centre (SDSC), Sriharikota located in the south-eastern part of India is the space port of India that is being used as rocket launching station by the Indian Space Research Organisation (ISRO). Optical signatures formed in the lower and upper atmosphere after the rocket exhaust plumes accompanying rocket launches made from SDSC have been observed and recorded by television camera for many years. However, observations and analysis of rocket exhaust plumes from satellite-mounted imager for Indian launchers have not been carried out for investigating atmospheric phenomena occurring in the lower atmosphere.

In this paper, a scientific study has been carried out with an objective to analyse the dynamics of rocket exhaust plumes during its initial trajectory in the troposphere and lower stratosphere for estimation of atmospheric wind vectors, using the observations acquired from satellite-mounted imaging camera on-board a geostationary platform.

Data Used and Methodology

Present study deals with detecting, tracking, and studying the dynamics of rocket plume produced in the initial trajectory by the Geosynchronous Satellite Launch Vehicle (GSLV) MK-II F11 rocket carrying the GSAT-7A payload. GSAT-7A is an advanced communication satellite of ISRO for providing wide range of service spectrum from low bit rate voice to high bit rate data communication to the users over a wide oceanic region of India including the Indian land mass. This particular launch took place from the second launch pad of SDSC located in Sriharikota island (13.7331°N, 80.2047°E) on 19 December, 2018 at 16:10 IST. Sriharikota is a barrier island off the Bay of Bengal coast located in the state of Andhra Pradesh of India. The geographical location of SDSC, Sriharikota is shown on a map of south India in Fig. 1.

In the present paper, rocket plume from the GSLV MK-II F11 vehicle is studied at its initial trajectory through analysis of series of images captured from an imaging camera namely, Geo-imaging High Resolution Camera (GHRC) on-board GSAT-29 satellite. The GHRC is an experimental instrument on-board GSAT-29 geostationary satellite located at 55°E on equator. GHRC can image earth disc in six multi-spectral bands located within visible-near infrared region (Band1: 460 to 520 nm, Band2: 506 to 594 nm, Band3: 620 to 680 nm, Band4: 696 to 736 nm, Band5: 768 to 849 nm, Band6: 814 to 870 nm) through frame camera configuration. Nominal spatial resolution at nadir is 54 m. Nominal specifications including the spectral characteristics of GHRC instrument are summarised in the Table 1. Out of six spectral bands, two of the GHRC spectral bands are new entry to the Indian Earth Observation payload configuration. These are (1) red-edge band (696–736 nm) and (2) near infrared band (814–870 nm). The set of six spectral bands has its unique advantage for observing the earth's surface in the atmospheric window region, which provides enhanced observation capability especially for the vegetation monitoring.

A specific GHRC imaging session was planned to capture the launch of GSLV MK-II F11 rocket carrying the GSAT-7A payload on 19 December, 2018 around 16:10 IST. Continuous imaging of same frame having an area of the dimensions 110 km × 110 km containing the SDSC launch pad and adjoining area of Bay of Bengal was carried out in the near-infrared band 4 (NIR: 768 to 849 nm). NIR band is chosen here for analysis because NIR radiation is absorbed by water quite strongly as compared to the visible radiation and thus NIR band observations offer a significant contrast between the rocket exhaust plume and background water surface. A total of 2211 image frames of NIR band were acquired by GHRC sensor around the launch event.

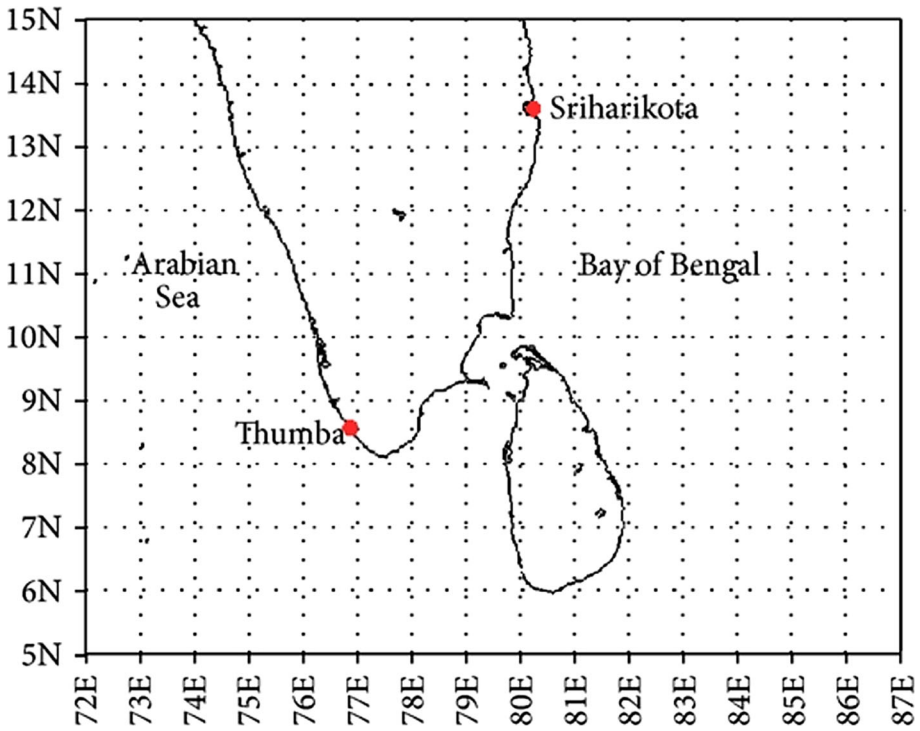

Fig. 1 Geographical location of ISRO's rocket launching centre, Satish Dhawan Space Centre (SDSC), Sriharikota shown on the map of South India

Table 1 Specifications of GHRC instrument on-board GSAT-29

Parameter	Value	Remarks
Altitude (km)	35,786	Geosynchronous orbit
Satellite location	55° E	On equator
Spectral bands (nm)	Band1: 460 to 520	Filter wheel based
	Band2: 506 to 594	
	Band3: 620 to 680	
	Band4: 768 to 849	
	Band5: 696 to 736	
	Band6: 814 to 870	
Ground sampling distance (m) @ nadir	54 (nominal)	200 (product level)
Swath (km) @ nadir	110 × 110	In a single snap
System saturation	100% albedo	
SNR at 100% albedo	> 100	With appropriate exposure setting for each band

Our analysis consists of three major steps, (a) processing 2211 image frames captured by GHRC; (b) tracing and investigation of initial rocket plume produced by the GSLV vehicle from all the images, and (3) detailed analysis of dynamics of exhaust plume in the lower atmosphere. The space launcher injected the GSAT-7A payload into an intended Geosynchronous Transfer Orbit of 170.8 km × 39,127 km 19 min after the lift-off. The time period between launch and the deposition of the plume in the lower and upper atmosphere is generally between 1 and 4 min. The rocket plumes were studied at the initial trajectory of the launch vehicle within first 2 min after the launch. The frame data corresponding to the rocket plume were processed and analysed for understanding the properties of lower atmosphere in terms of estimating wind profile.

A flow chart of methodology incorporated in this study is shown in Fig. 2. All the 2211 images were registered to a common geographical reference, so that these images can be analysed and inter compared. On visual interpretation, it was observed that rocket exhaust plume after launch was first detected at frame number 538 and the rocket left the

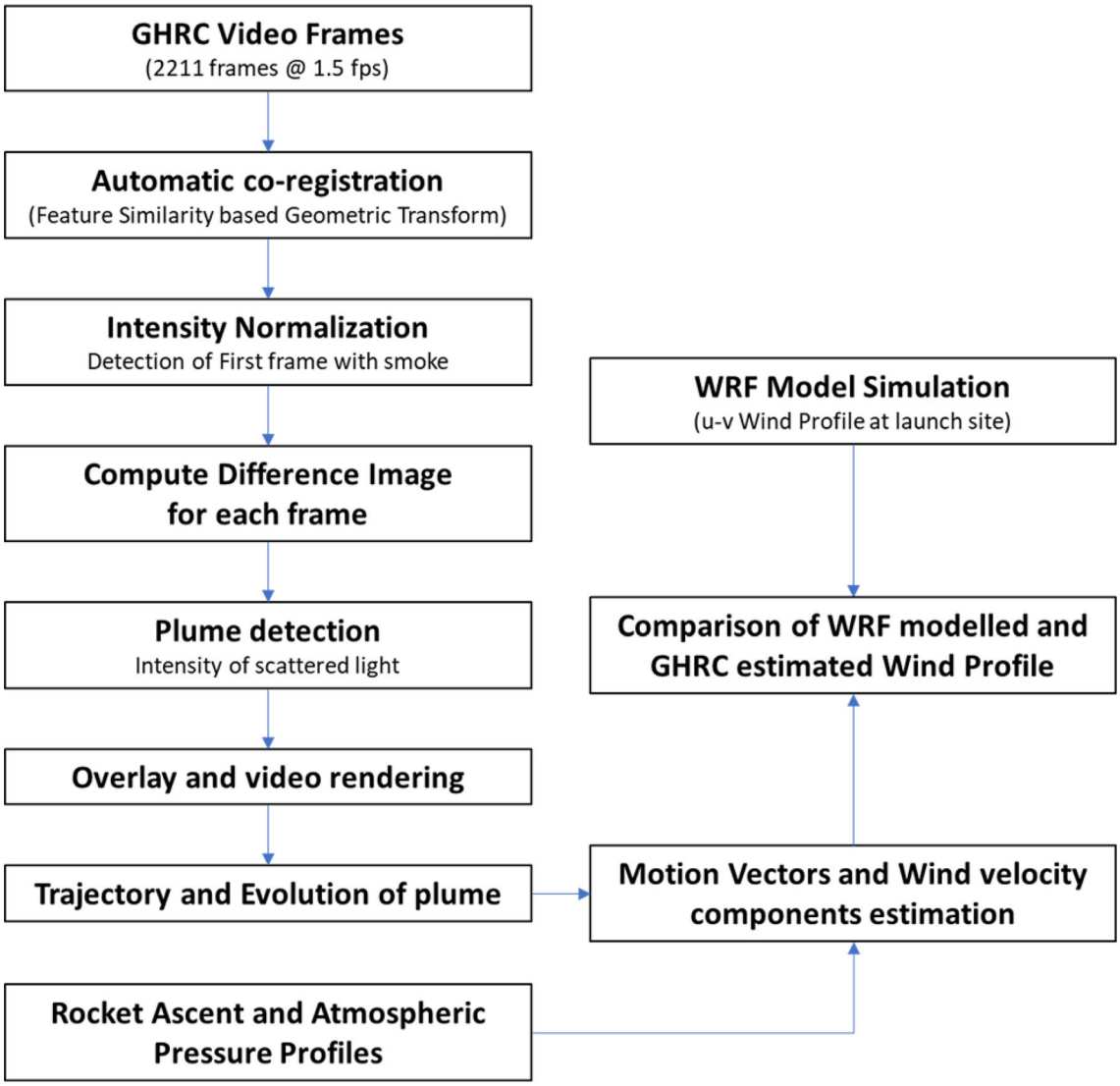
GHRC Video Frames
(2211 frames @ 1.5 fps)
Automatic co-registration
(Feature Similarity based Geometric Transform)
Intensity Normalization
Detection of First frame with smoke
Compute Difference Image for each frame
Plume detection
Intensity of scattered light
Overlay and video rendering
Trajectory and Evolution of plume
Rocket Ascent and Atmospheric Pressure Profiles
WRF Model Simulation
(u-v Wind Profile at launch site)
Comparison of WRF modelled and GHRC estimated Wind Profile
Motion Vectors and Wind velocity components estimation

Fig. 2 Flowchart of methodology incorporated in this study

subset under study in frame number 652. Using a frame rate of ~ 0.66 s/frame or 1.5 frame per second (fps), the rocket left the study area 76 s after launch. GSAT-7A ascent trajectory was estimated from graphs available in public broadcast stream of the launch event. A time vs altitude profile was obtained and correspondingly this altitude was converted to atmospheric pressure at rocket altitudes.

Location of rocket in frame numbers 538 to 652 was obtained and related to the atmospheric pressure level at which the rocket's exhaust plumes were deposited. These points were taken as starting points for tracking the motion vector of smoke plume. Using image differencing technique, smoke plume was detected starting from frame number 538 and overlaid on the original image for comparison. Time evolution of rocket exhaust was studied up to frame number 1200 and dispersion of smoke plume was traced to identify the end points for motion vector. Wind velocity components (u and v) were computed from smoke plume motion vectors using Eqs. 1 and 2.

$$u_e = \frac{x_f - x_i}{f_f - f_i} \times fps \times \Delta x \tag{1}$$

$$v_e = \frac{y_f - y_i}{f_f - f_i} \times fps \times \Delta y \tag{2}$$

where (x_i, y_i) and (x_f, y_f) are starting and ending pixel co-ordinates of the motion vector respectively, f_i and f_f are initial and final frame numbers corresponding to plume evolution at that pressure level, fps is the video frames per second, and Δx and Δy are spatial resolution in horizontal and vertical directions in the image plane, respectively.

Weather Research and Forecasting (WRF) modelled wind profile was obtained for 1730 h IST and compared with wind profile estimated using our motion vectors from

smoke plume evolution. The WRF model is a meso-scale numerical weather prediction model which is widely used for atmospheric research and operational forecasting applications (Powers et al., 2017; Skamaroch et al., 2008). U and V components of wind velocity at 3 h intervals over 35 different pressure levels were obtained from WRF v3.9 run over and around Sriharikota for 19 December, 2018 at approximately 5 km grid resolution.

Results and Discussion

Detailed analysis of sequential images shows that the plume begins appearing in the image around five hundred and thirty-eighth frame as seen in Fig. 3a (with background image) and Fig. 3d (without background). The rocket exhaust plume can be seen in each of the frames of GHRC images due to the dark background of Bay of Bengal water in NIR band. For clarity, background was removed using image differencing and plume intensity was converted to a colour shade (blue colour corresponds to low intensity, while red-brown colour corresponds to high intensity of scattered radiation). A clear full appearance of plume is seen in the six hundred and fifty-second frame (Fig. 3b and e), which corresponds to one hundred and fourteenth frame after the launch, i.e. 76 s after launch. This particular one hundred and fourteenth frame corresponds to an altitude of approximately 18.34 km (derived from GSLV launch profile), which means the rocket would have reached an altitude of 18.34 km from the surface of the Earth. Time vs rocket altitude as obtained from public broadcast stream of GSLV F11 launch event is shown in Fig. 4a and rocket altitude vs corresponding ambient atmospheric pressure is shown in Fig. 4b. Taking frame number 538 as T0 and tracking the movement of rocket in the subsequent frames, we were able to compute rocket altitude and ambient pressure at each frame where the smoke was deposited. As the rocket moved eastwards and ascended through the atmosphere, each pixel along the rocket plume corresponded to a different altitude and subsequently a different pressure level.

Analysis of the rocket exhaust plume within the image frame was carried out using the series of GHRC images captured around the rocket launch time. As we can see in Fig. 3, a distinct exhaust plume starts appearing in the frame number 538 just after launch (Fig. 3a and d), which touches the end of image in the frame number 652 with the rocket leaving the frame (Fig. 3b and e). So, the plume remains in the image for 114 frames, corresponding to a total time duration of approximately 76 s, covering the full duration of plume's appearance in the image after the launch to exit from the image. Within first 700 frames after launch, when plume data were investigated in detail, it showed a very important atmospheric feature. An apparent shearing of the plume trail shape was observed between 652 and 852 frames which became prominent in

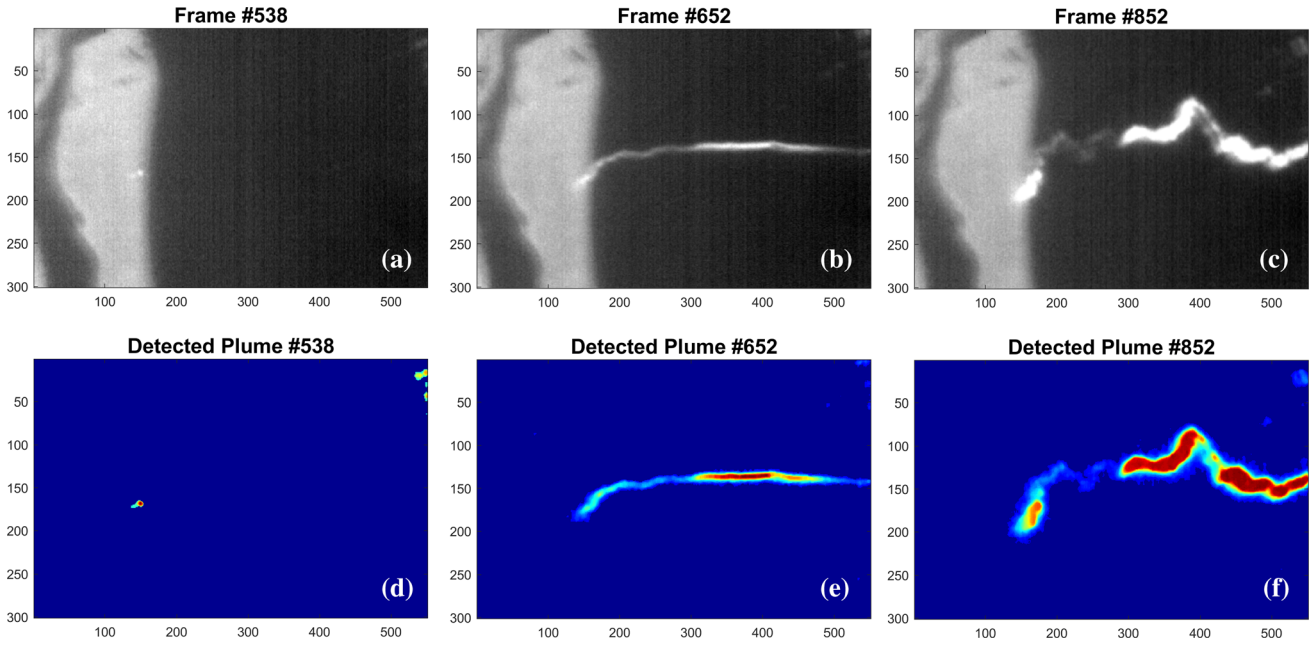

Fig. 3 Image corresponding to frame number **a** 538, **b** 652, and **c** 852 out of 2211 frames. Frame 538 corresponds to first detection of rocket plume in the video, frame 652 shows rocket leaving the study area, and frame 852 shows the diffusion of exhaust plume due to atmospheric winds. Detected plume and its intensity shown for frame number **d** 538, **e** 652, and **f** 852 corresponding to 0, 76, and 207 s post lift-off

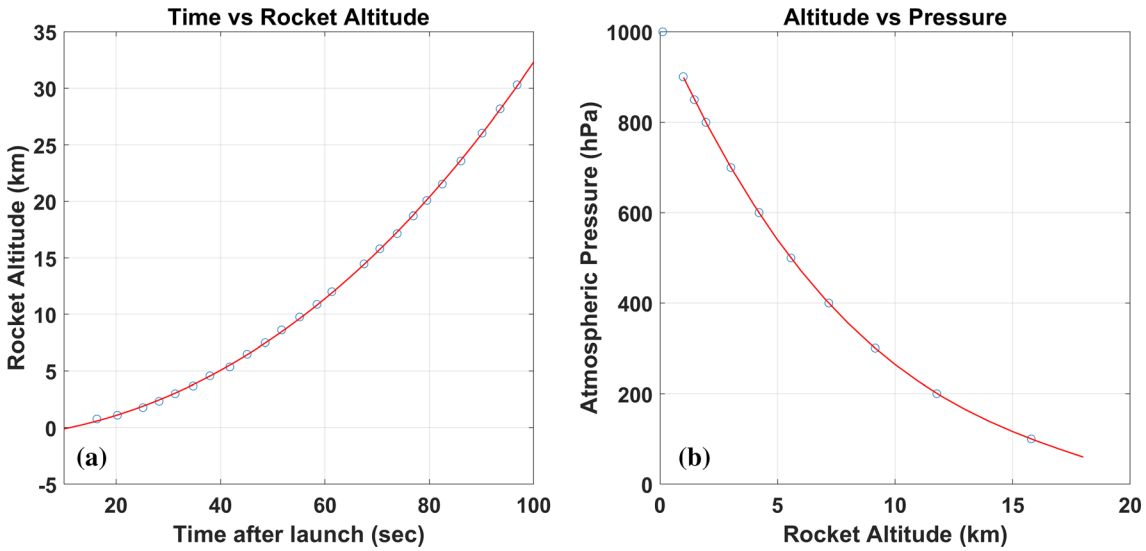

Fig. 4 **a** GSLV Mk-II F11 rocket altitude as a function of time. T0 is taken as lift-off time and first detection of rocket plume in GHRC frame. **b** Altitude vs ambient atmospheric pressure over launch site in Sriharikota

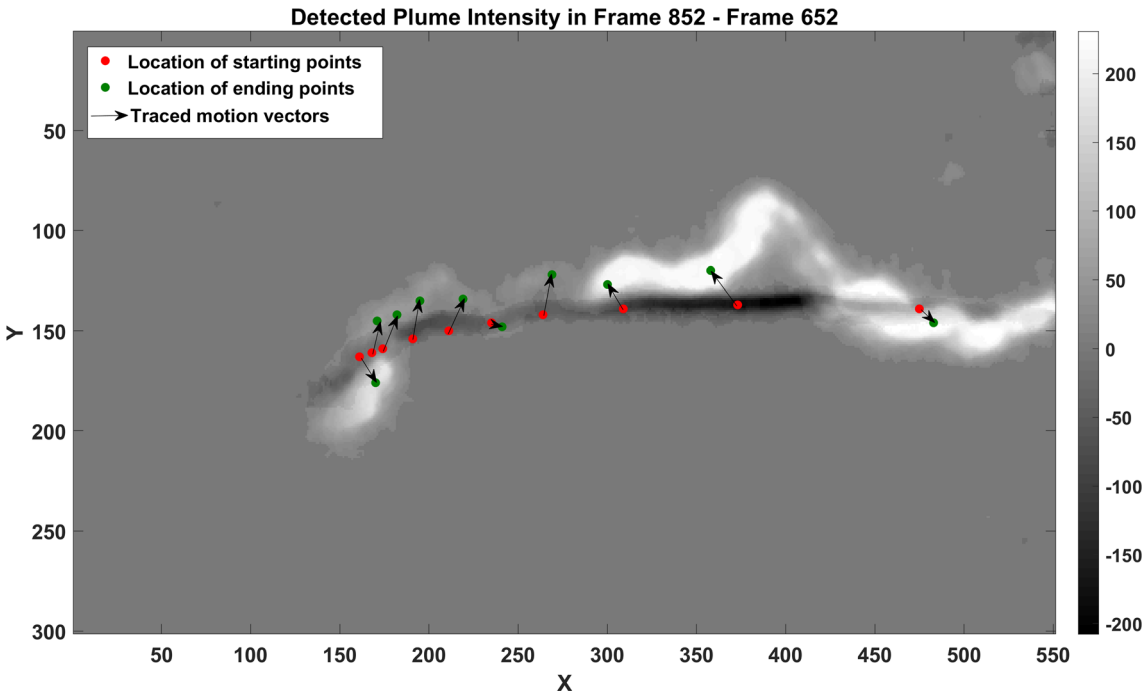

Fig. 5 Traced motion vectors of detected plume at ten pressure levels along the rocket's trajectory overlaid on intensity difference image of frame # 852—frame # 652

subsequent frames. Shearing of the plume trail from its original path is clearly seen and change of shape in plume trail can be observed after sometime (e.g. shearing of plume trail is shown in frame number 852 in Fig. 3c and f). By critically analysing the launch profile shown in Fig. 4, it can be said that 76 s after launch the rocket would have travelled approximately 18.3 km above the surface, which corresponds to 55 hPa at the site in the lower stratosphere. This means that analysis of rocket exhaust plume from the satellite data picked an important atmospheric phenomena—shearing of winds within the lower atmosphere of the Earth.

Wind motion vectors were generated using the time evolution of rocket plume in the troposphere and lower

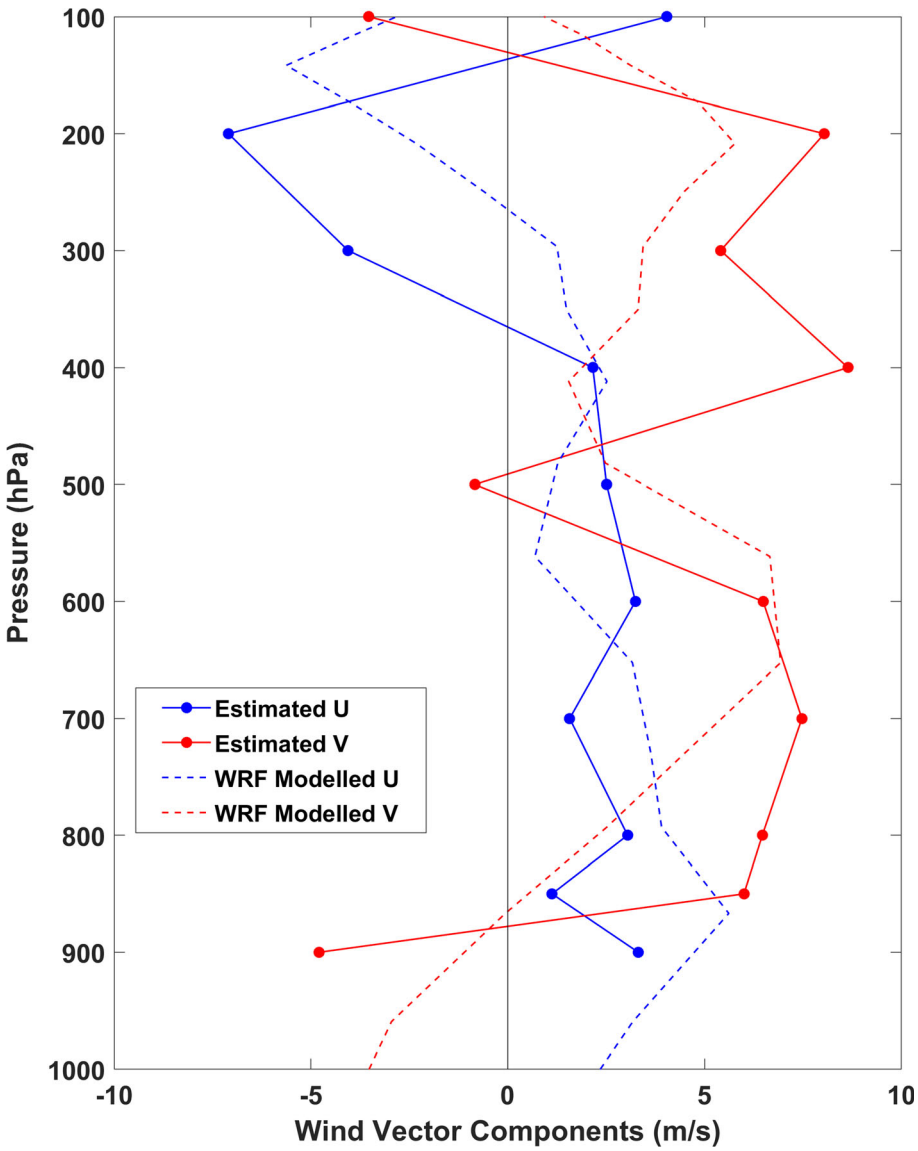

Fig. 6 Comparison of GHRC estimated u and v components of wind profile with WRF modelled wind between 900 and 100 hPa for 19 December, 2018 at 1730 h IST

stratosphere. Rocket trajectory was computed between frames 538–652 and rocket position in these frames were extracted which corresponded to different atmospheric pressure levels. These locations were taken as starting points for tracing atmospheric wind vectors. As the rocket ascends vertically for few seconds after launch, it was not possible to obtain the evolution of smoke plume near surface. However, as the rocket starts to steer horizontally towards east, we were able to pick the evolution of rocket exhaust in the x–y plane between 900 and 100 hPa pressure levels.

Rocket plume in every fiftieth frame after launch (T0) was extracted and compared with the initial trajectory to trace the motion of smoke plume. Those points which showed higher diffusion of smoke plume were removed, as it was difficult to trace their motion. Remaining points which showed clear features were kept for analysis and traced to determine the end points of plume motion vector. Using Eqs. 1 and 2, components of wind velocity along x (u) and y (v) direction were estimated. Figure 5 shows the traced motion vectors of rocket plume at selected pressure levels. GHRC estimated U component of wind ranged from − 7.1 m/s at 200 hPa to + 4.0 m/s at 100 hPa with lower values close to surface. V component of wind ranged from − 4.8 m/s at 900 hPa to + 8.6 m/s at 400 hPa with intense shear between 200 and 100 hPa levels.

In order to validate these observations, Weather Research & Forecasting (WRF) model was run over Sriharikota site by considering the input parameters corresponding to the time and day (19 December, 2018) of the launch. WRF derived u and v components of wind between 1000 and 100 hPa pressure levels over the launch site were analysed and plotted against the estimated wind profile from GHRC images (Fig. 6). The direction of estimated

wind at different pressure levels matched well with WRF model. However, wind speeds showed some deviations mainly because we are comparing fine resolution wind profile with coarse resolution modelled estimates at 5 km grid resolution. Even then, the modelled and estimated wind speeds showed similarities up to 500 hPa level. Significant deviation between u component of model and estimated winds was observed between 300 and 100 hPa pressure levels. Wind profile obtained from GHRC showed a clear change in direction of V component between 200 and 100 hPa with a strong shear between these levels. However, WRF model did not pick this change in direction of wind, which clearly shows the advantage of GHRC observation and its importance in wind profile study.

This demonstrates a novel use of high-frame observation capability of GHRC for some of the unique applications in the field of atmospheric studies. For the first time in India, we have analysed the dynamics of rocket exhaust during initial trajectory in the lower atmosphere using satellite-mounted imaging camera taken from the geostationary platform. This study also demonstrates the unique capability of GHRC for acquiring high-temporal datasets, which can be useful in large-scale smoke/plume detection and associated applications.

Conclusion

In this study, we present new observation of an orbital rocket's exhaust plume from a geostationary platform and use this high-temporal video data to understand vertical wind profile near the launch site. Exhaust plume from the launch of GSLV Mk-II F11 rocket from Sriharikota, India was observed from GSAT-29's Geo-imaging High Resolution Camera (GHRC) payload, which provided a unique dataset for atmospheric observation and helped in estimating atmospheric wind profile. This is the first time in India where a rocket launch was observed from geostationary camera and its video frames were analysed to estimate u and v components of wind velocity at different altitudes in the troposphere and lower stratosphere. GHRC estimated U component of wind ranged from − 7.1 m/s at 200 hPa to + 4.0 m/s at 100 hPa with lower values close to surface. V component of wind ranged from − 4.8 m/s at 900 hPa to + 8.6 m/s at 400 hPa with intense shear between 200 and 100 hPa levels. Comparative analysis of the results obtained from satellite data with Weather Research and Forecasting (WRF) modelled wind fields showed a good match. GHRC was able to pick the strong shear and change in wind direction with height between 200 and 100 hPa which wasn't observed in model simulations. This unique imaging capability of GHRC could be used to study similar phenomena which require very high-temporal resolution such as large-scale smoke/plume detection and other atmospheric applications.

Acknowledgements Authors would like to thank Shri Nilesh M Desai, Director SAC, Dr. I M Bahuguna, Deputy Director, EPSA, Dr. B K Bhattacharya, Group Director, BPSG-EPSA and Dr. R P Singh, Group Director, GHCAG-EPSA for their encouragement and support to this study. Authors would like to acknowledge Dr. A K Dubey, Scientist, LHD-EPSA-SAC for providing WRF model outputs for the study area.

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